# Neutrinos from Black Hole Accretion Disks

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# Explosions of massive stars

Core can collapse to:

- a protoneutron star

  discussed in talks by M. Giannotti, H. Duan, A. Friedland, J. Kneller, C. Cardall, J. Baker, etc.

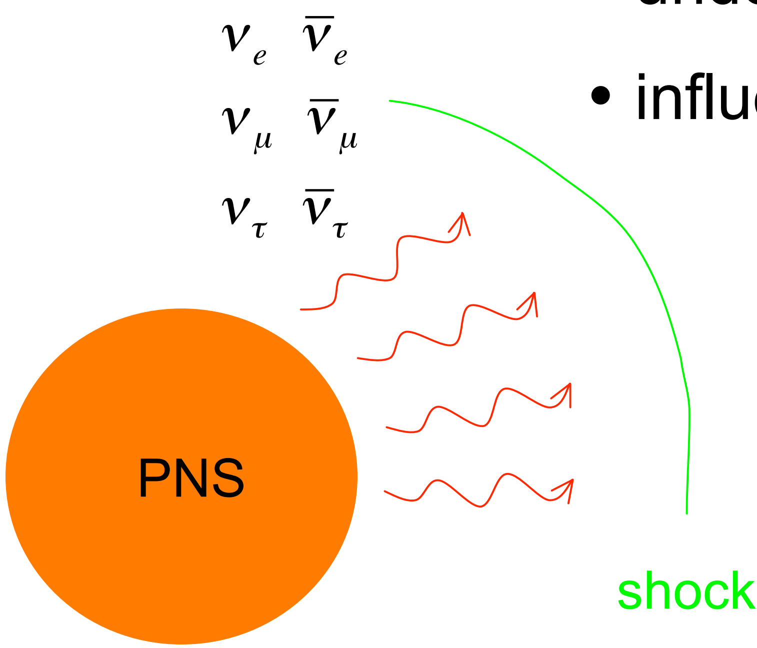
- a black hole surrounded by an accretion disk

  collapsar model (Woosley ‘93, MacFadyen and Woosley ‘99)
  long-duration gamma-ray bursts, x-ray flashes

# Neutrinos from the protoneutron star

All types of neutrinos are emitted from the protoneutron star (PNS) core. As the neutrinos travel through the outer layers of the star, they

- undergo flavor transformations
- influence the nucleosynthesis




The energy ranges of the emitted neutrinos are roughly:

$$\langle E_{\nu_\mu} \rangle = \langle E_{\nu_\tau} \rangle = \langle E_{\bar{\nu}_\mu} \rangle = \langle E_{\bar{\nu}_\tau} \rangle = 20 - 30 \text{ MeV}$$

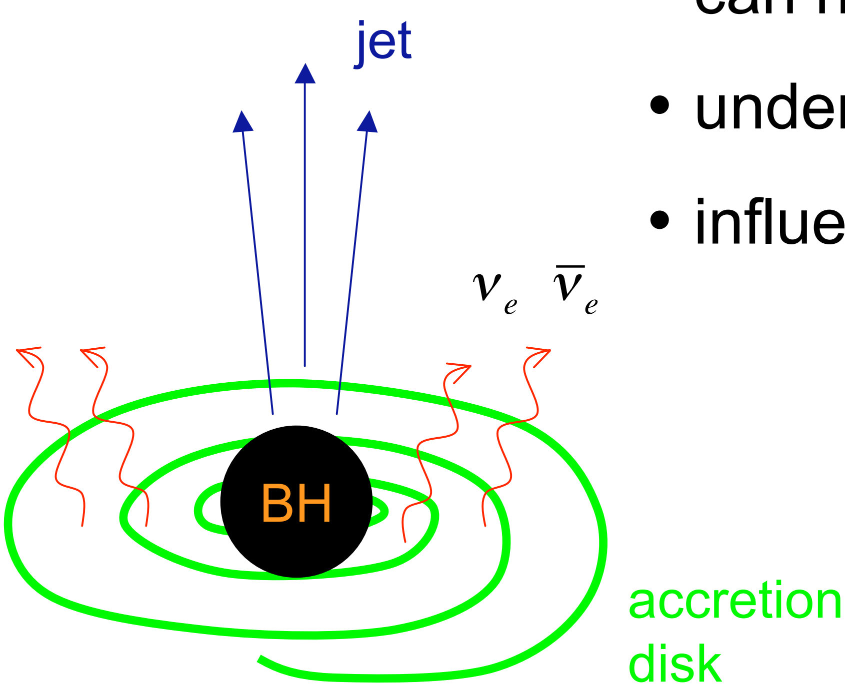
$$\langle E_{\bar{\nu}_e} \rangle = 13 - 19 \text{ MeV}$$

$$\langle E_{\nu_e} \rangle = 8 - 13 \text{ MeV}$$

# Neutrinos from a black hole accretion disk

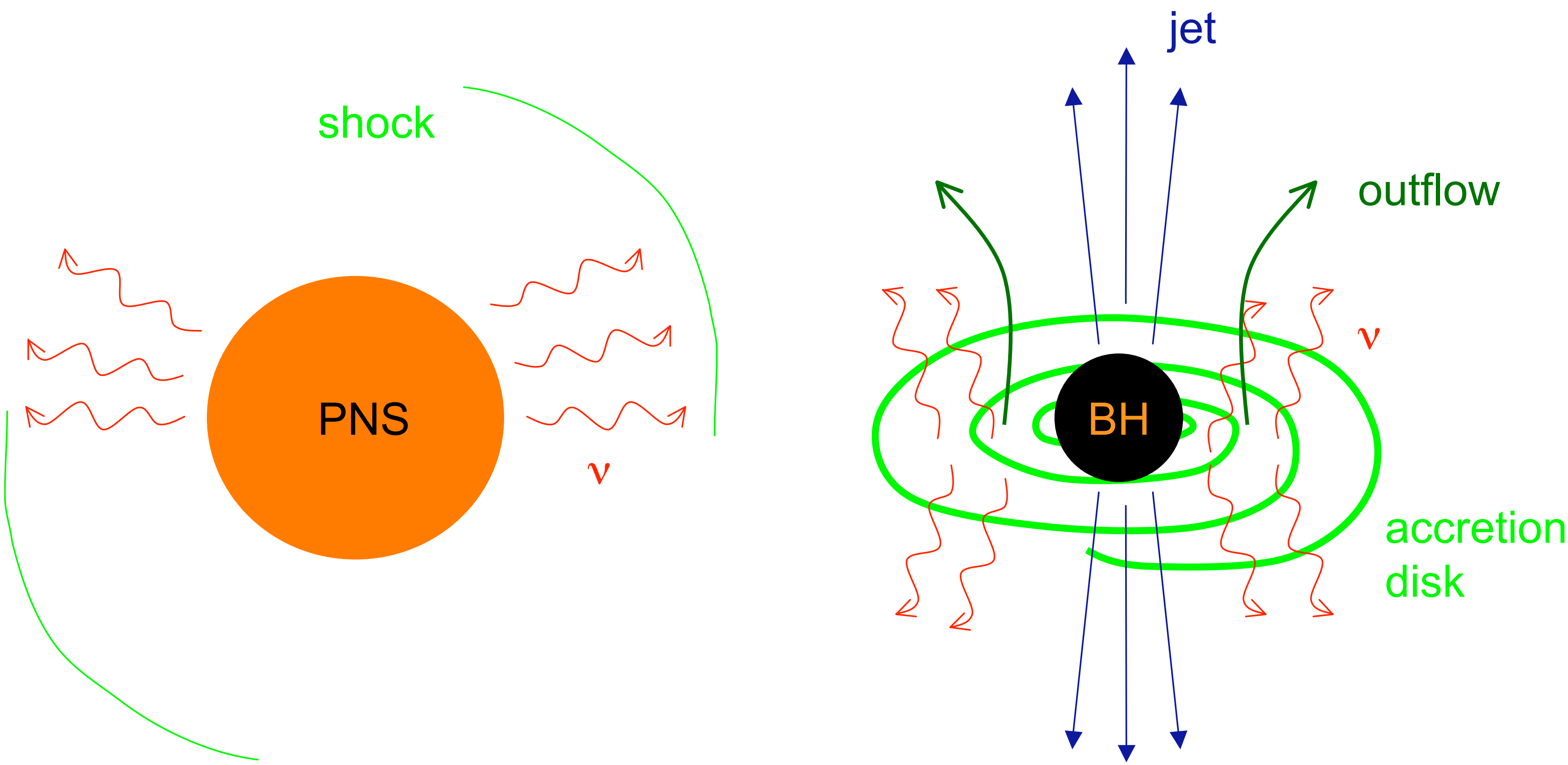
Neutrinos are emitted from the accretion disk around the black hole (AD-BH). As the neutrinos travel outwards from the disk, they

- can help power the jet
- undergo flavor transformations
- influence the nucleosynthesis

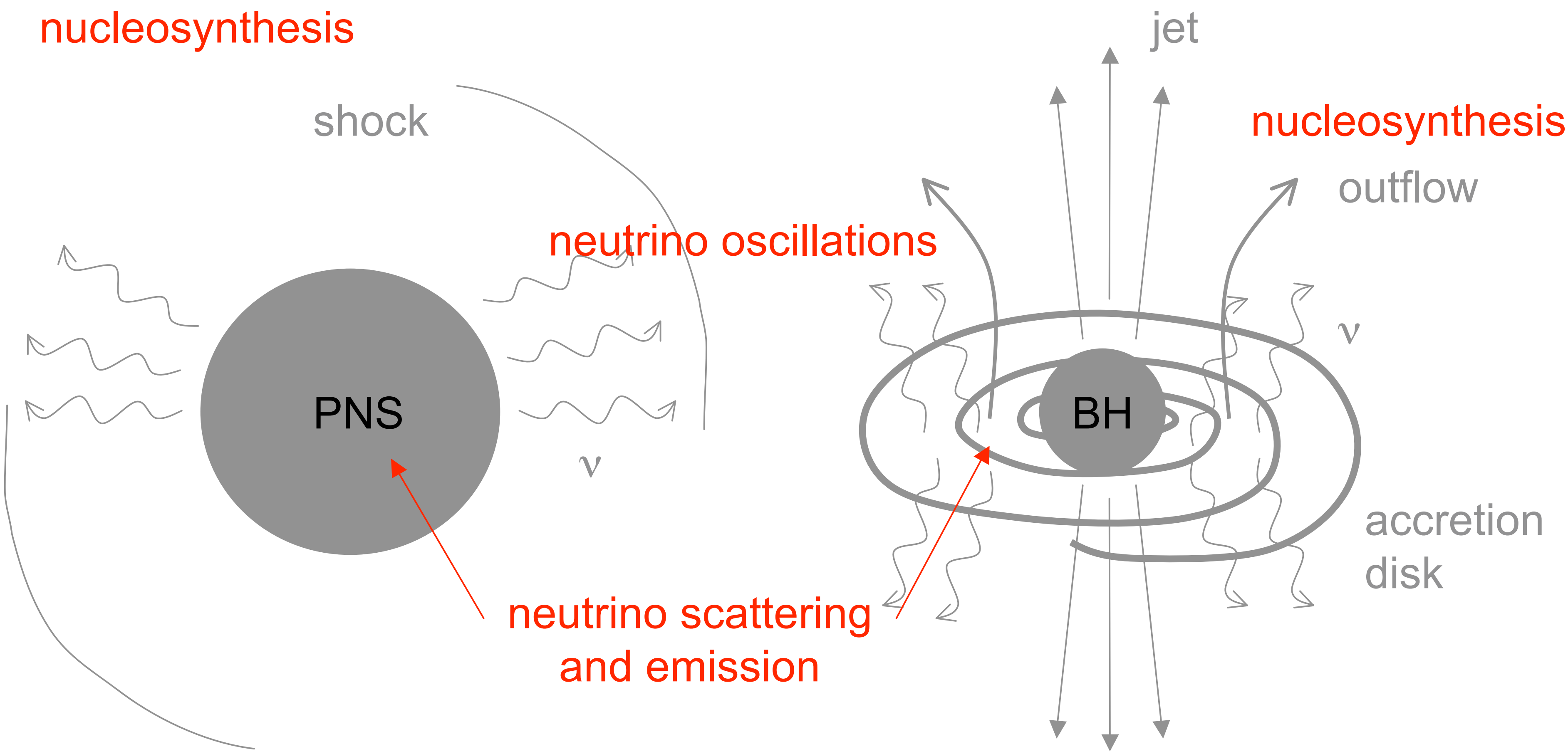



Mass accretion rate ~ fractions of solar masses per second ($\dot{m}$ = 1 $M_\odot$/s)

# PNS – AD-BH comparison



# PNS – AD-BH neutrino physics



# Galactic core-collapse supernovae

- Occur every 30-50 years
- Expect $3\times10^{53}$ ergs in neutrinos
- Neutrinos can be seen in SuperK, KamLAND, MiniBooNE
- Neutrinos will be used to constrain core collapse models

Will the next galactic supernova produce neutrinos from a protoneutron star or an accretion disk around a black hole?

# PNS or AD-BH - how can we tell?

- Total energetics

  PNS: ~$3\times10^{53}$ ergs in neutrinos

  AD-BH: for a $3M_\odot$ black hole,

  $(9(M/M_\odot)\times10^{53}$ ergs binding energy) x (fraction emitted in $\nu$)

  where $M$ = mass of material processed in disk

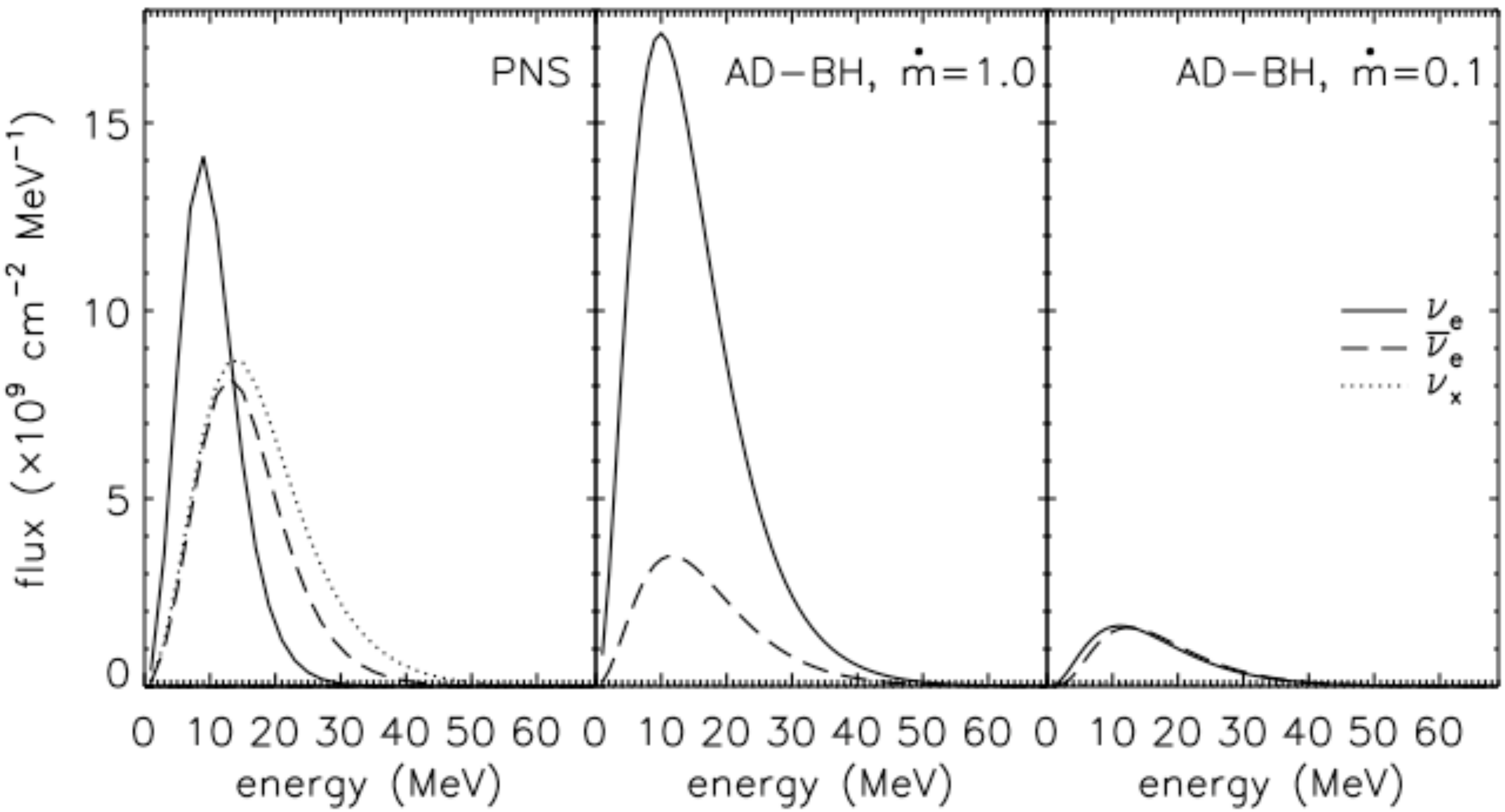
- Time scale of emission

  PNS: neutrino luminosity decays as $e^{-t/\tau}$ over ~10 s

  AD-BH: disk steady state?

- Flavor content

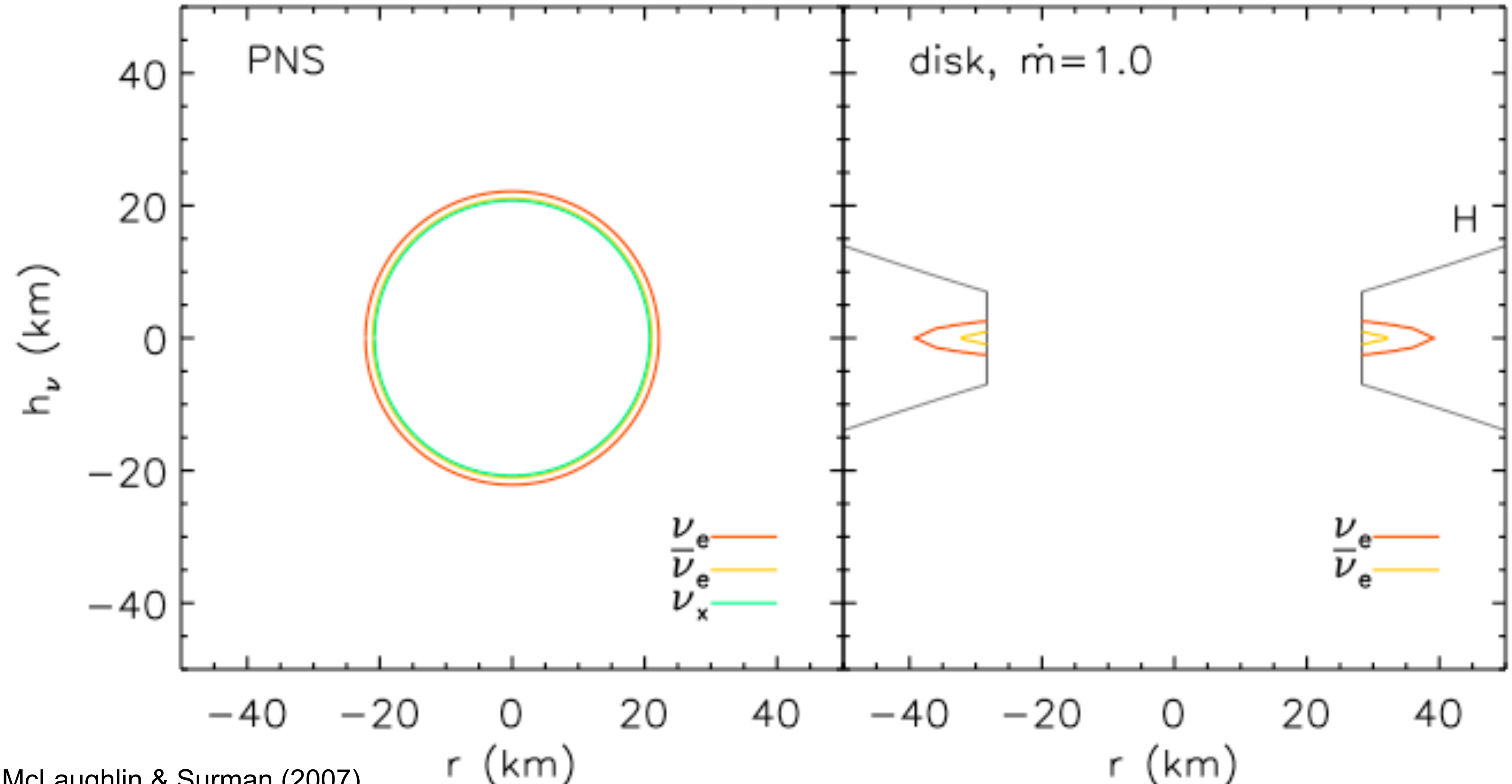
# Comparison of emitted neutrino spectra




McLaughlin & Surman (2007)

Spectra (no oscillations) at 10 kpc

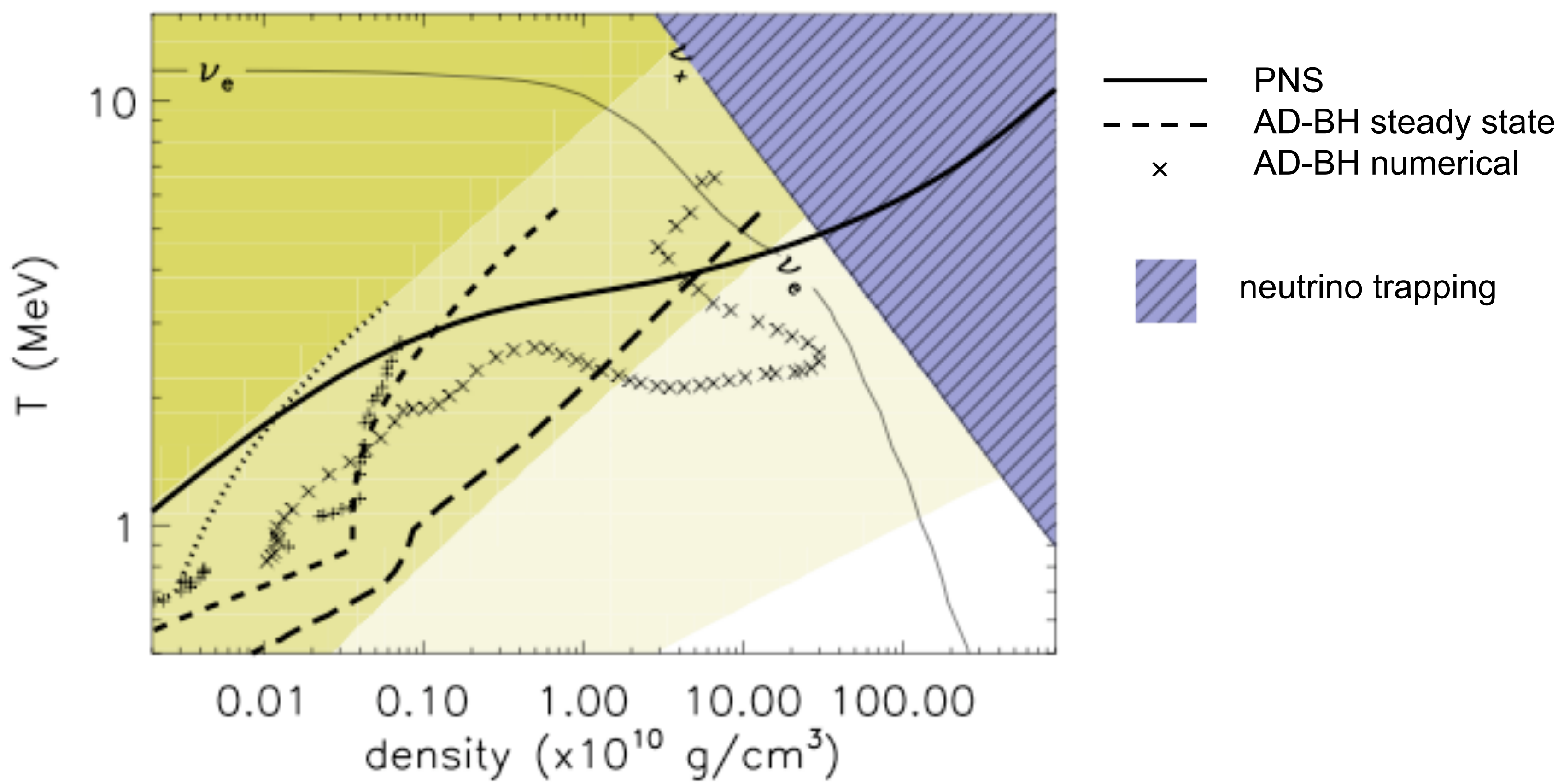
# Neutrino decoupling surfaces




McLaughlin & Surman (2007)

$\nu_\mu,\ \bar{\nu}_\mu,\ \nu_\tau,\ \bar{\nu}_\tau$ not trapped in the AD-BH

# Neutrino trapping




McLaughlin & Surman (2007)

# Neutrino oscillations

By far the largest detection cross section is in

$$\bar{\nu}_{\mathrm{e}} + p \rightarrow e^{+} + n$$

Two options:

1. All cases besides 2.: $\sim (1/3)\bar{\nu}_{\mathrm{e}}$'s transform to $\bar{\nu}_{\mu}, \bar{\nu}_{\tau}$

2. Inverted hierarchy, large $\theta_{13}$: all $\bar{\nu}_{\mathrm{e}}$ transform to $\bar{\nu}_{\mu}, \bar{\nu}_{\tau}$

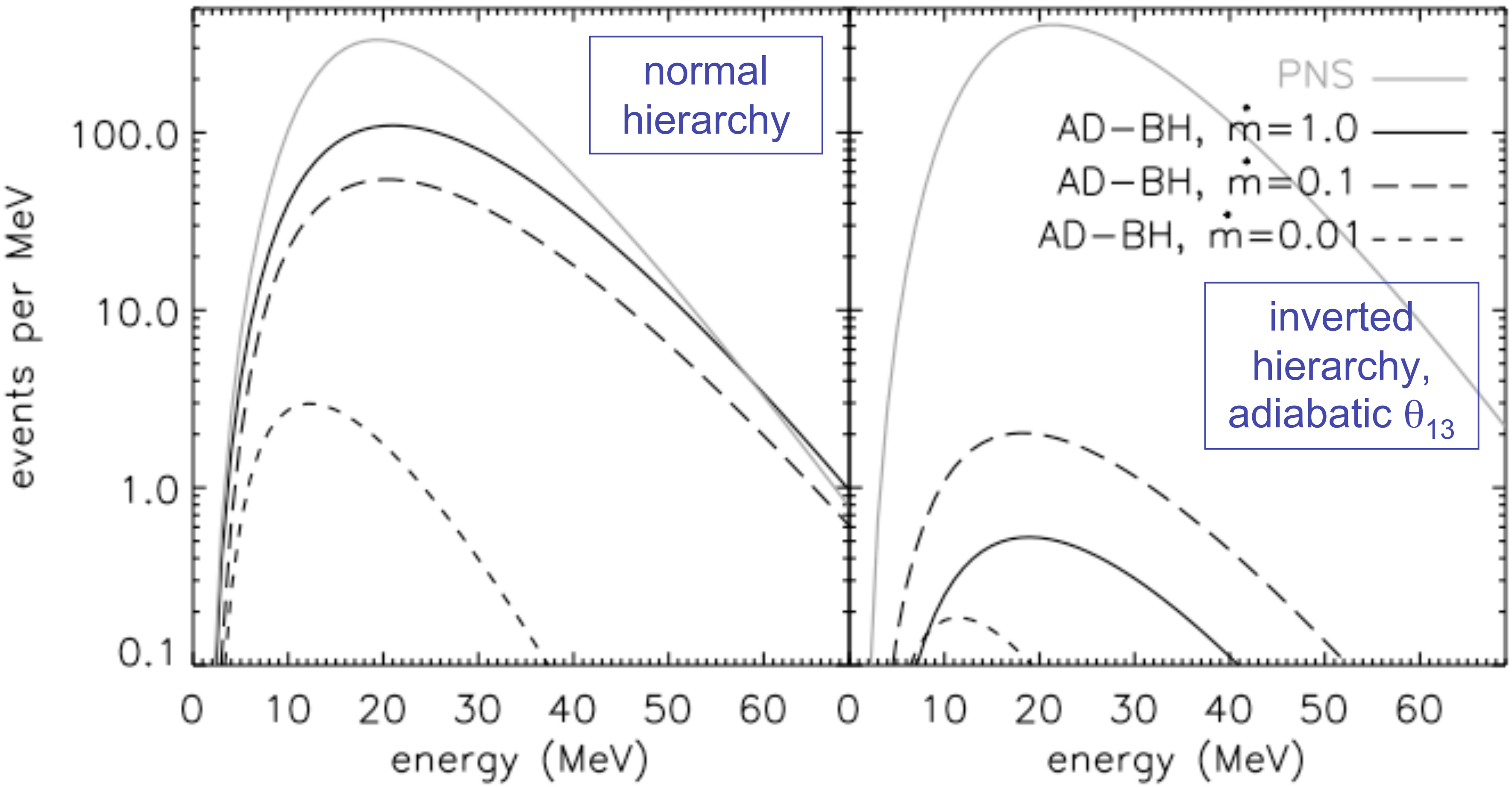
PNS These options produce similar results, to the extent that the spectra of $\bar{\nu}_{\mathrm{e}}$ are similar to the spectra of $\bar{\nu}_{\mu}, \bar{\nu}_{\tau}$.

AD-BH These options produce very different results:

1. Large $\bar{\nu}_{\mathrm{e}}$ signal

2. Greatly reduced $\bar{\nu}_{\mathrm{e}}$ signal

# Estimated events in SuperK




McLaughlin & Surman (2007)

# Neutral current flux

ratio of neutral current to charged current flux

| Oscillation scenario 1: | Oscillation scenario 2: |
|---|---|
| • PNS 7 : 1 | • PNS 6 : 1 |
| • AD - BH $\dot{m} = 0.01$ 3 : 1 | • AD - BH $\dot{m} = 0.01$ 40 : 1 |
| • AD - BH $\dot{m} = 0.1$ 3 : 1 | • AD - BH $\dot{m} = 0.1$ 70 : 1 |
| • AD - BH $\dot{m} = 1.0$ 8 : 1 | • AD - BH $\dot{m} = 1.0$ 1600 : 1 |

McLaughlin & Surman (2007)

# Neutral current signal at SuperK

Detection via

$$\nu + {}^{16}\mathrm{O} \rightarrow \nu + {}^{15}\mathrm{O} + n$$

$$\nu + {}^{16}\mathrm{O} \rightarrow \nu + {}^{15}\mathrm{N} + p$$

${}^{15}\mathrm{N}$ and ${}^{15}\mathrm{O}$ decay by characteristic emission of gamma rays

Langanke et al (1995)

Expected counts :

- PNS 30
- AD - BH $\dot{m} = 0.01$ 0.3
- AD - BH $\dot{m} = 0.1$ 3
- AD - BH $\dot{m} = 1.0$ 20

For one solar mass processed by the disk

McLaughlin & Surman (2007)

# Other options for a neutral current signal

- KamLAND

$$\nu + p \rightarrow \nu + p$$

detect recoil of proton (Beacom et al)

- Proposed lead detector

$$\nu + \mathrm{Pb} \rightarrow \nu + \mathrm{Pb} + n$$

$$\nu_e + \mathrm{Pb} \rightarrow e^- + \mathrm{Bi} + n$$

- Heavy water detector (like SNO)

# Galactic core-collapse supernovae

How can we tell if the next galactic supernova emits neutrinos from a PNS or an AD-BH?

The total energetics and/or timescale of emission will likely differ

A robust and immediate distinction between the two is the difference in flavor of the emitted neutrinos

Due to the influence of neutrino oscillations, a good neutral current signal measurement is essential to make this distinction

# AD-BH nucleosynthesis prospects

GRB rate ~ 1-5 x $10^{-5}$ per galaxy per year
(rate higher in early universe?)

But AD-BH may be more common:

X-ray flashes (XRF) ~10x rate of GRBs

'Failed' GRBs?

One to several solar masses are processed in an AD-BH
$\Rightarrow$ Models suggest up to half of this material may be ejected from the system

AD-BHs may therefore be important contributors to some rare species

# Nuclear species of interest

Nickel - 56

observed in long-duration GRB afterglows

light *p*-process ($^{74}Se$, $^{78}Kr$, $^{84}Sr$, $^{92}Mo$, $^{94}Mo$, etc.)

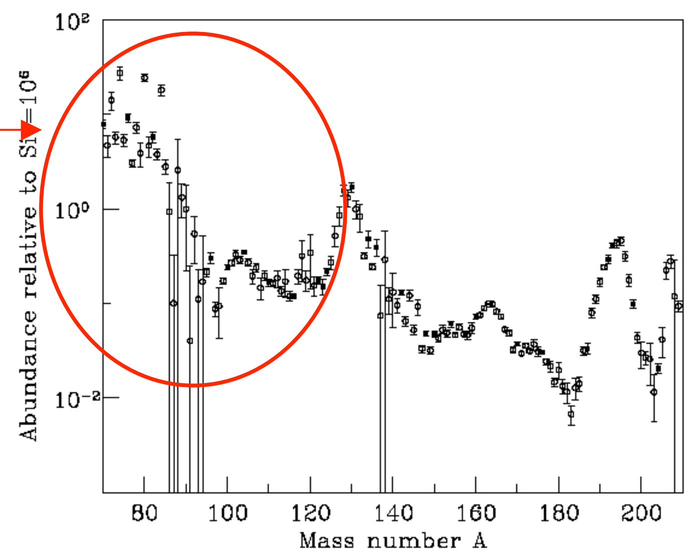
can perhaps be made in supernovae by

- fine tuning $Y_e$
- neutrino interactions on nuclei (Fuller and Meyer)
- late time neutrino interactions on nucleons (Frohilch et al, Pruet et al)

weak *r*-process

observations of metal-poor halo stars suggest the main component of r-process (2nd and 3rd peaks) likely has a supernova origin (Cowan, Truran et al, Sneden et al)

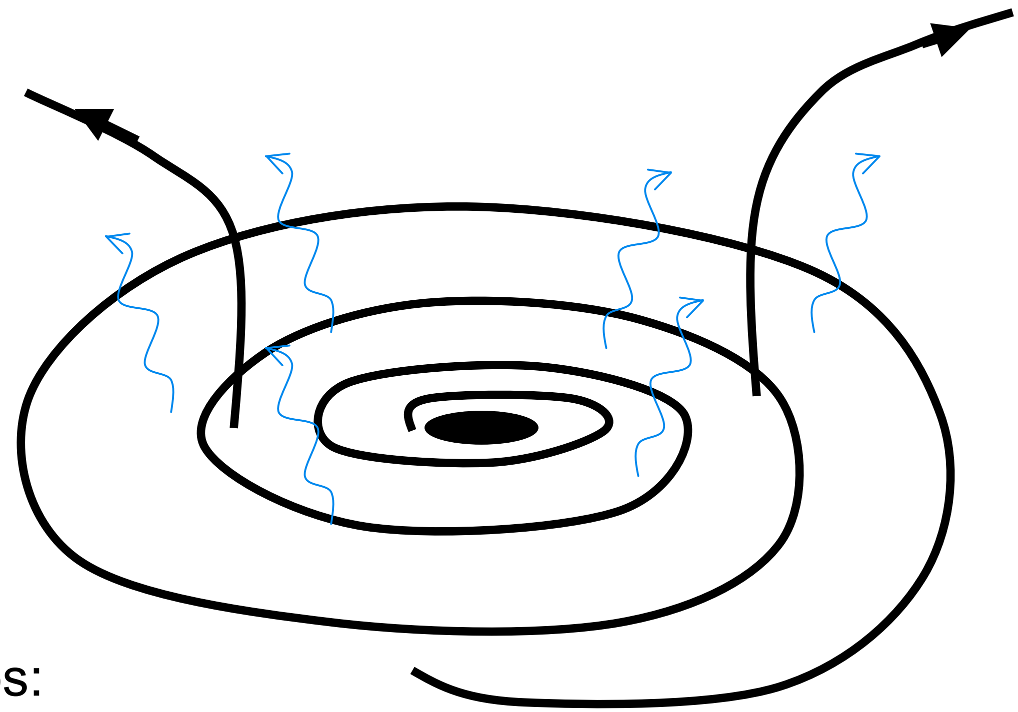
site of production of light *r*-process nuclei?



# Neutrinos and nucleosynthesis in AD-BH outflows

Follow material

- through disk
- as ejected in outflow



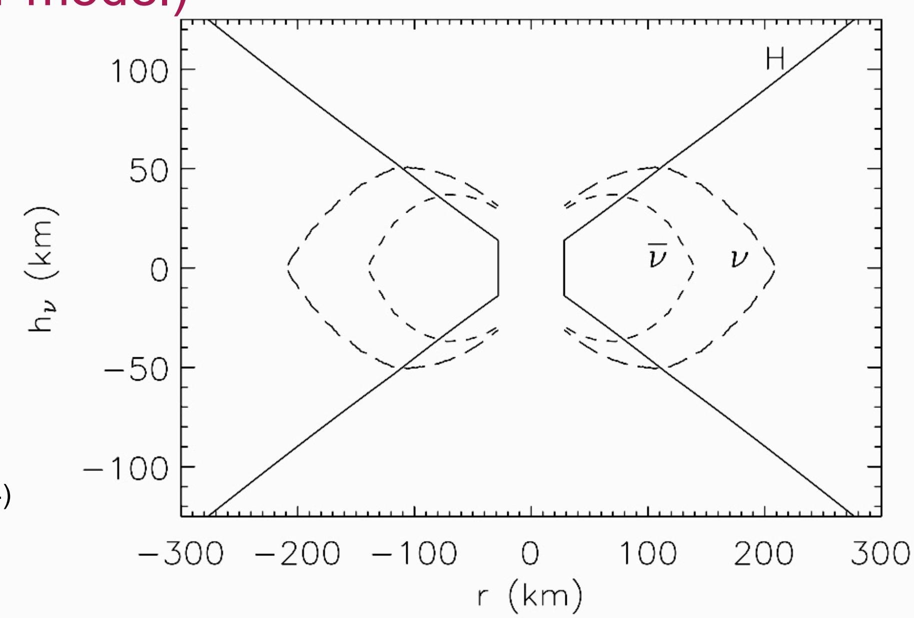
Importance of neutrinos:

Weak reactions set neutron-to-proton ratio, which determines subsequent nucleosynthesis

# Neutrinos and nucleosynthesis in AD-BH outflows

- Low accretion rate disks (collapsar model)
  Neutrino fluxes due (almost) entirely to electron/positron capture in disk
  electron neutrino flux > electron antineutrino flux
  – Neutrinos drive the material proton rich

- High accretion rate disks (merger model)
  Neutrinos become trapped in the inner regions
  – Hotter antineutrinos drive the material neutron rich




Surman & McLaughlin (2004)

# Our nucleosynthesis calculation

## 1. Disk conditions

We start with available black hole accretion disk models:

- DiMatteo, Perna, and Narayan (2002; DPN)
- Chen and Beloborodov (2006; CB)

We calculate the disk composition and the neutrino/antineutrino fluxes from disk

## 2. Outflow hydrodynamics

Adiabatic flow (10 < *s/k* < 50) with velocity as a function of radial distance:

$$u = v_\infty \left(1 - \frac{R_o}{R}\right)^\beta$$

with $v_\infty \sim$ 10,000 km/s, 0.2 $< \beta <$ 2.6

## 3. Nuclear recombination in the outflow

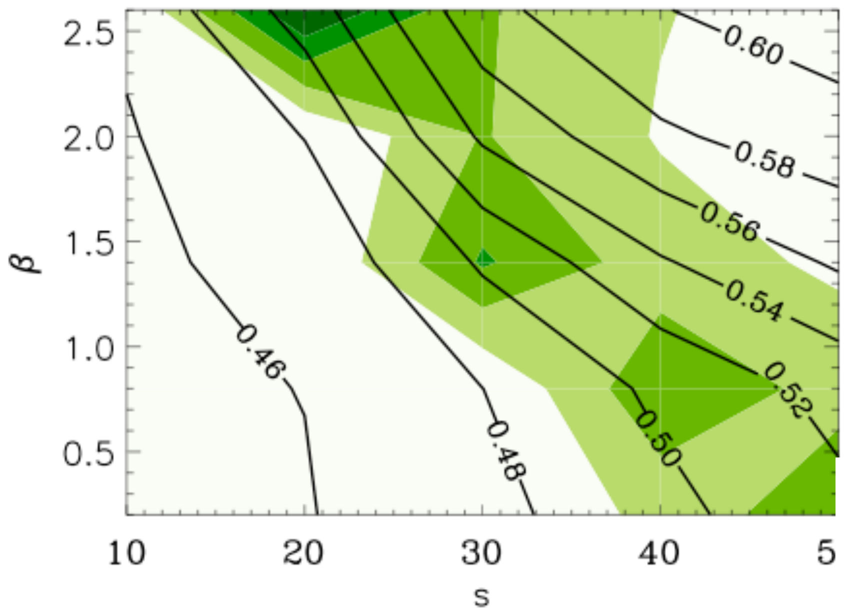
Full nuclear network code:

W. R. Hix, *J. Comp. Appl. Math*., 109, 321 (1999) (J. Beun, R. Surman)

*r*-process nucleosynthesis code:

J. Walsh, B.S. Meyer, R. Surman

# Ni-56 production




$$\dot{m} = 0.1$$

$$a = 0$$

CB disks

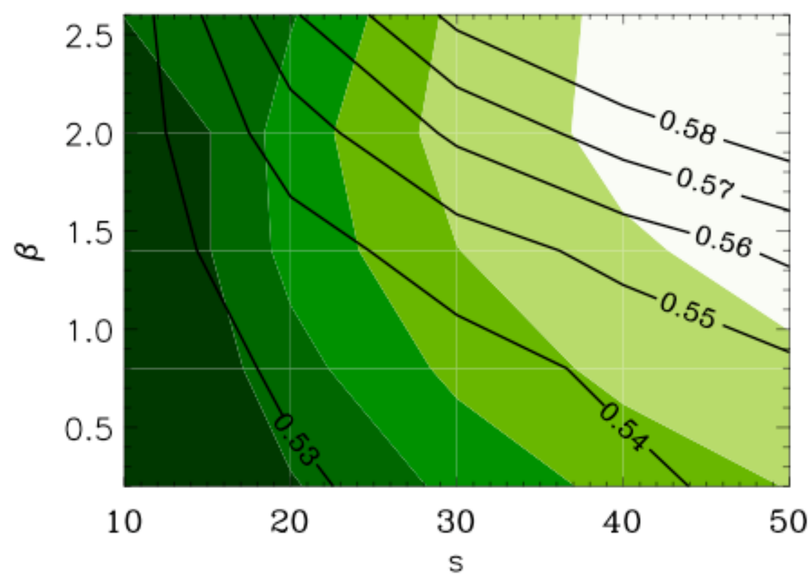
$r_o = 100$ km

$v_\infty = 0.1c$


$^{56}$Ni mass fraction

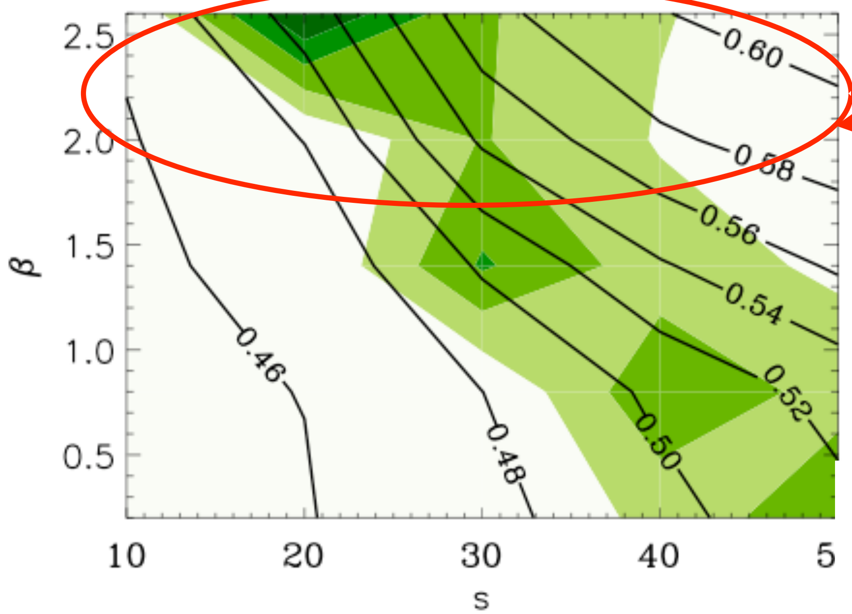
$$\dot{m} = 0.05$$

$$a = 0.95$$




Surman, McLaughlin, Chen, Beloborodov, & Hix, in preparation (2007)

# Ni-56 production




$\dot{m} = 0.1$

$a = 0$

influence of neutrinos

CB disk

$r_o = 100$ km

$v_\infty = 0.1c$


$^{56}$Ni mass fraction

$\dot{m} = 0.05$

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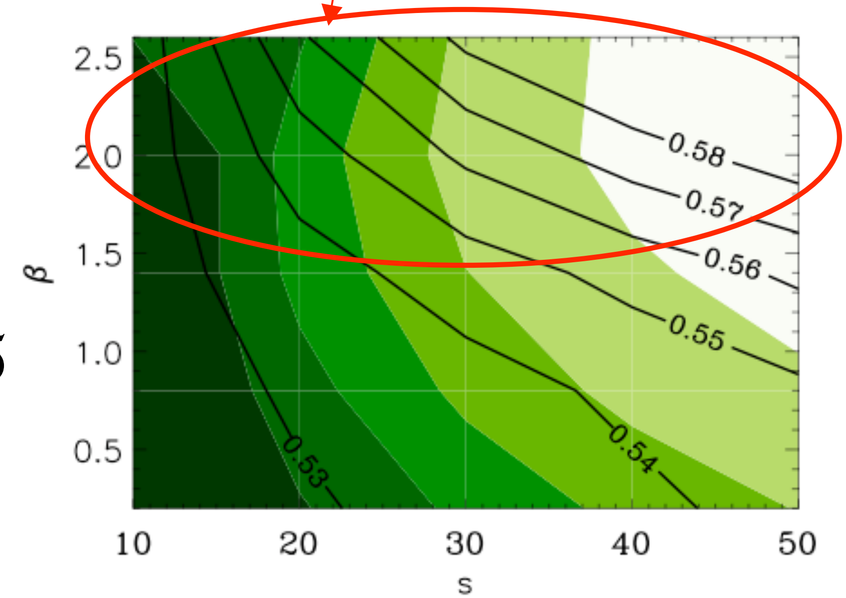
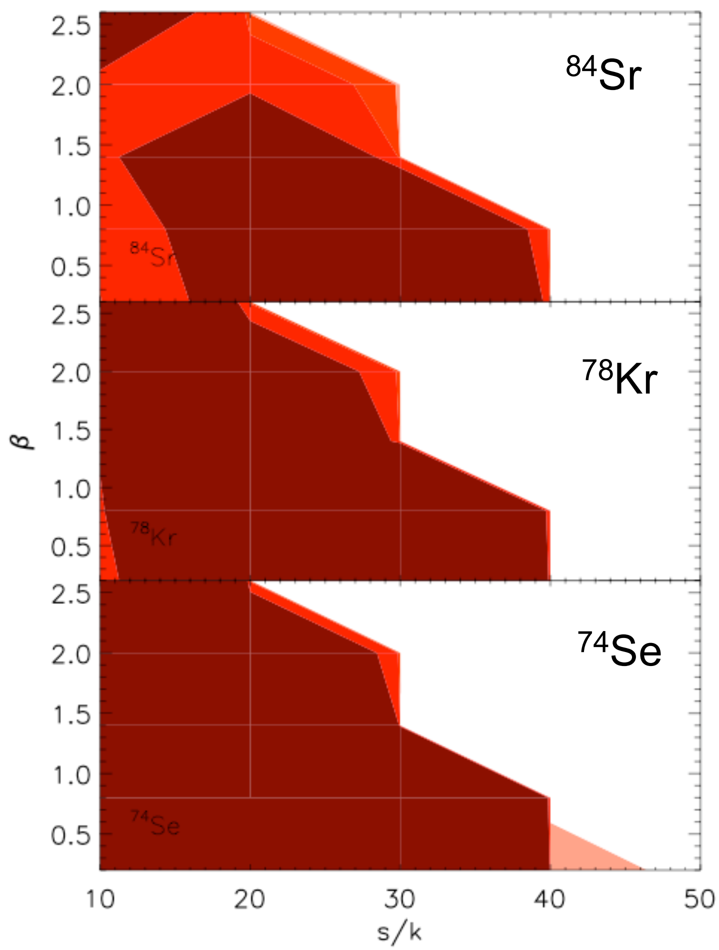
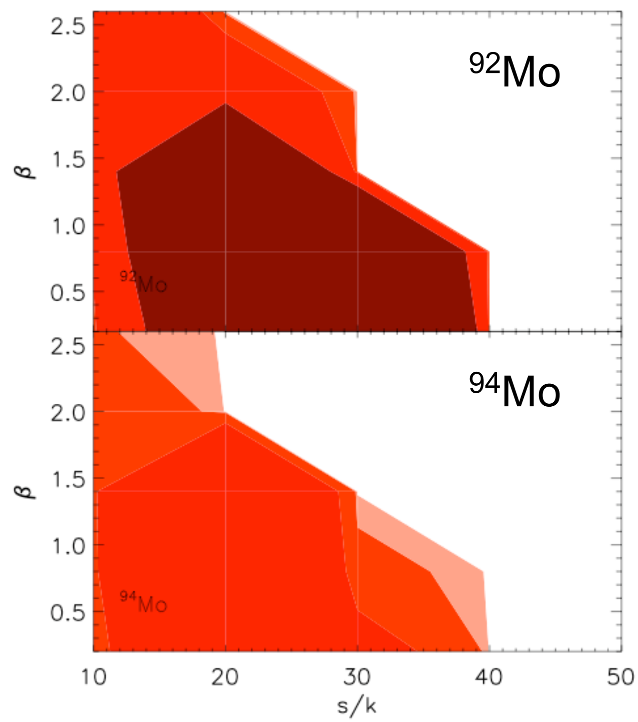



Surman, McLaughlin, Chen, Beloborodov, & Hix, in preparation (2007)

# Production of light *p*-nuclei




Surman, McLaughlin, Chen, Beloborodov, & Hix, in preparation (2007)




CB disk

$\dot{m} = 0.1$

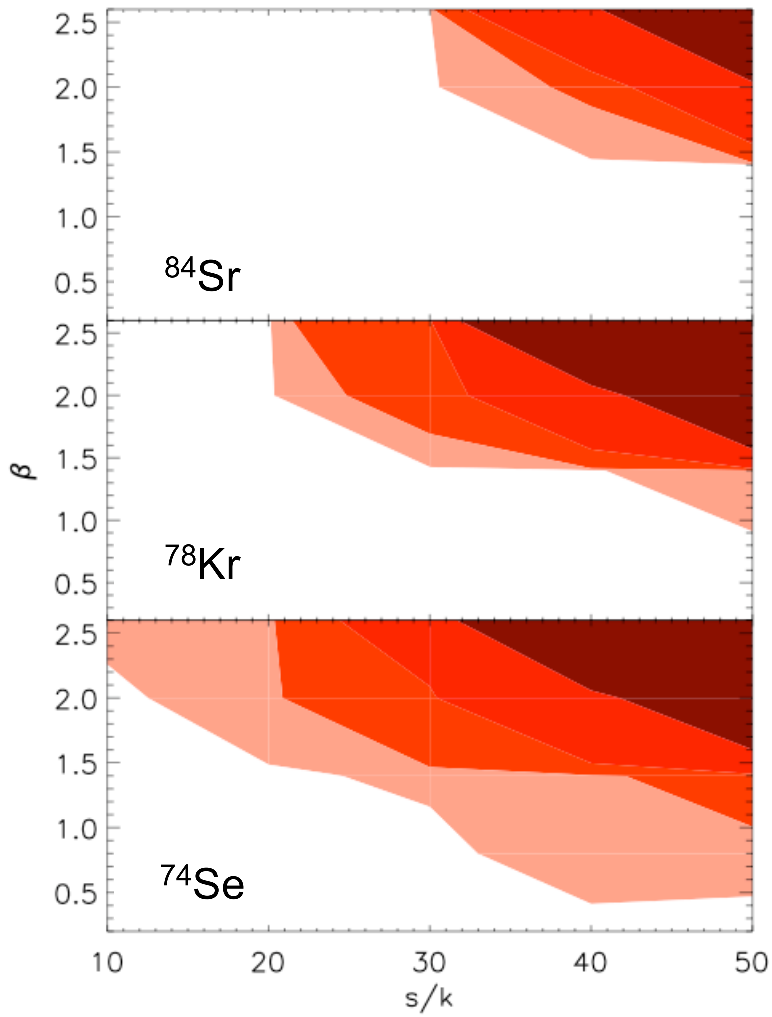
$a = 0$

$r_0 = 100$ km

$v_\infty = 0.1c$


$$O(j) = \left(\frac{M_{wind}}{M_{SN\ ejecta}}\right) \times \left(\frac{X_{wind}}{X_{solar}}\right)$$

# Production of light *p*-nuclei - $\nu p$-process?



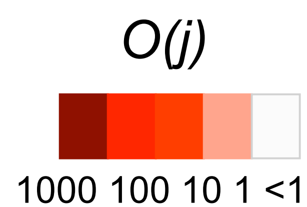

CB disk

$\dot{m} = 0.05$

$a = 0.95$

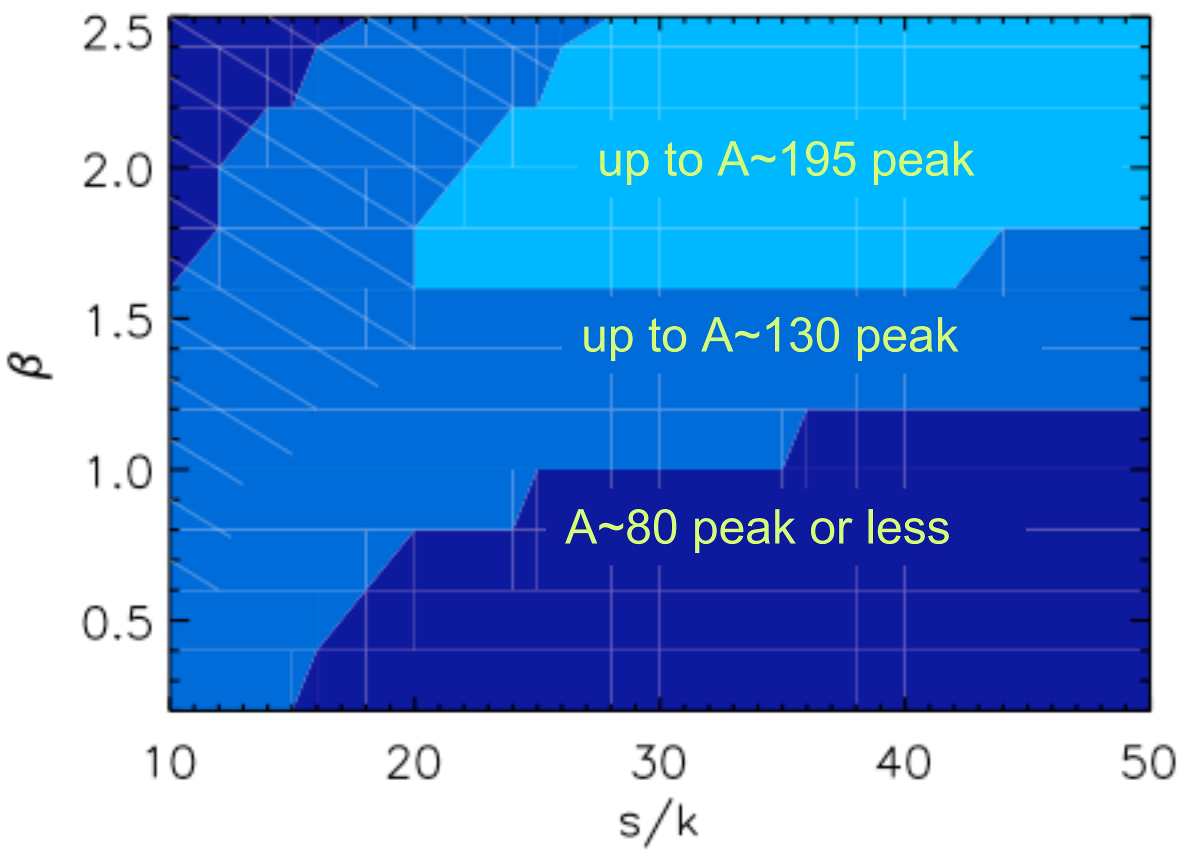
$r_0 = 100$ km

$v_\infty = 0.1c$




Surman, McLaughlin, Chen, Beloborodov, & Hix, in preparation (2007)

# Production of *r*-process nuclei




DPN disk

$\dot{m} = 10$

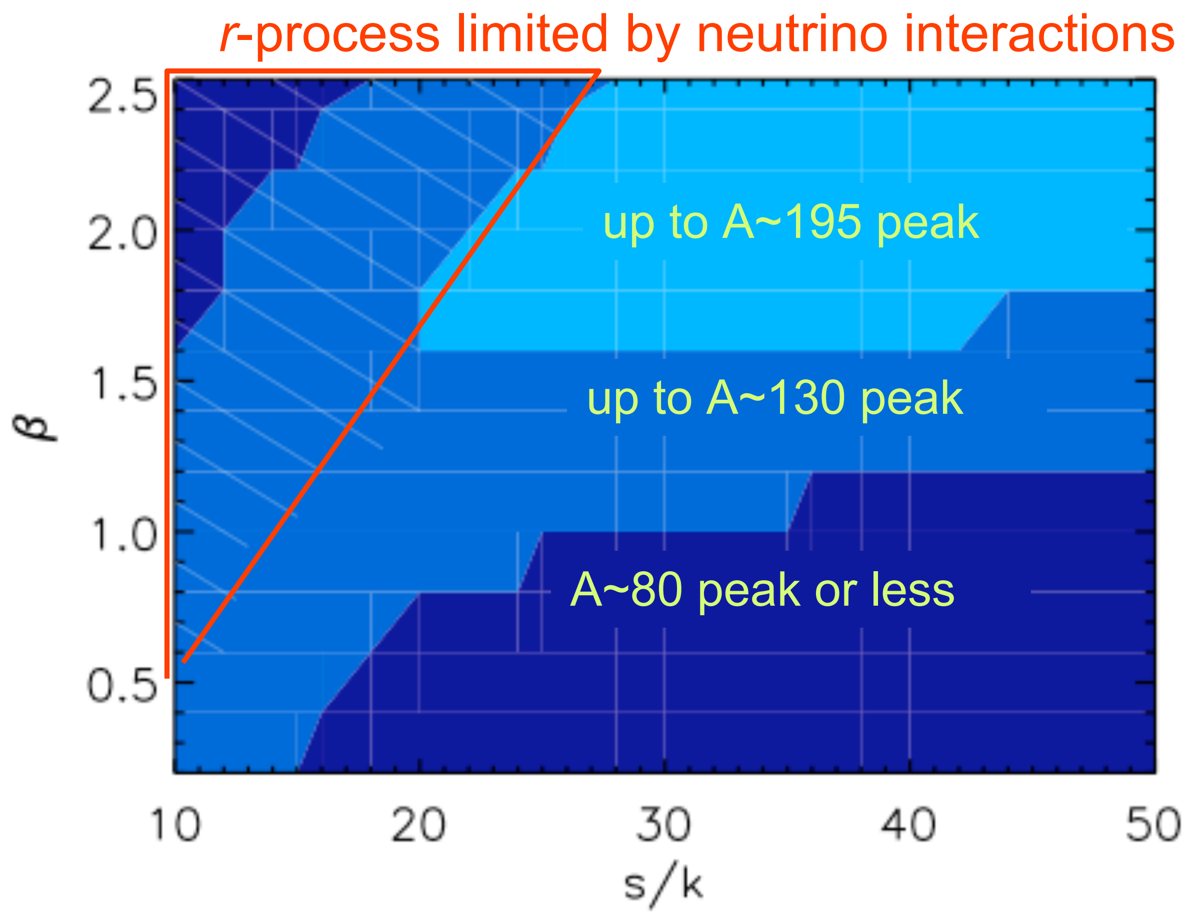
$a = 0$

$r_0 = 100$ km

$v_\infty = 0.1c$

Surman, Kane, & Smith, in preparation (2007)

# Production of *r*-process nuclei




DPN disk

$\dot{m} = 10$

$a = 0$

$r_0 = 100$ km

$v_\infty = 0.1c$

Surman, Kane, & Smith, in preparation (2007)

# Neutrinos and nucleosynthesis in AD-BH outflows

Given disk and outflow parameters, we can determine what nucleosynthesis will result from an understanding of the neutrinos

Nucleosynthesis in AD-BH outflows provides a promising mechanism for GRB nickel production

Additionally, AD-BH outflows may contribute to the galactic abundances of certain rare nuclear species, such as *r*-process nuclei or light *p*-process nuclei